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Mixing ratios of 2+–2+ transitions in even-even nuclei in the mass region $A = 122$–128

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With 7 figures in the text

ABSTRACT

Angular correlation measurements have been carried out on some even-even nuclei in the mass region $A = 122 - 128$ in an attempt to study the variation of the mixing ratio $E2/M1$ in $2+ - 2+$ transitions when a neutron or proton pair is added to the nucleus. The $2+ - 2+$ transitions discussed in this report have all been found to be of almost pure $E2$ character. The following nuclei were studied: Te^{122}, Te^{126}, Xe^{126}, and Xe^{128}.

Introduction

The angular correlation techniques are well suited for investigations of multipole characters of gamma transitions between excited states in atomic nuclei. We have used these techniques in an investigation of some $2+ \ - 2+$ transitions in even-even nuclei in the mass region $A = 122 - 128$. A summary of the results has already been given [1]. The purpose of the work has been to investigate the variation of the mixing parameter δ when a proton or neutron pair is added to the nucleus. δ represents the ratio of the matrix-elements of electric quadrupole and magnetic dipole radiation. The even-even type nuclei in this region are very well suited for mixing ratio determinations. The ground states have no angular momentum and the first excited levels have the spin assignment $2+$ as is the case in all even-even nuclei well apart from closed shells. In the nuclei studied in this work, Te^{122}, Te^{126}, Xe^{126}, and Xe^{128}, the second excited state is also a $2+$ state. These assignments as given by earlier experiments [2–7] are also confirmed by our correlation measurements. The nucleons are paired to give even parity in the ground states, and the rotational excitation does not give rise to any parity changes. Accordingly the cascades are of the $2+ \ - 2+ \ - 0+$ type where the upper transition is a mixture of electric quadrupole and magnetic dipole radiation and the lower transition has pure $E2$ character. It would have been most interesting to study the 723 kev–603 kev cascade in Te^{124}, too, but the level scheme [8] of Te^{124} is far too complicated both when fed from Sb^{124} and from I^{124} to be accurately measured using present scintillation spectrometer techniques.

Experimental arrangements

The apparatus used in the correlation measurements and the experimental methods have been described earlier [9]. As the measurements on Xe^{128} are reported in Ref. 9 we refer to this work for the experimental details. Some new changes were, however, made before the measurements on the isotopes Te^{122}, Te^{126}, and Xe^{126}, the most important one being a change to the fourteen stage photomultiplier RCA 6810 A.

The counters were shielded with lead collimators to avoid coincidences caused by Compton scattered quanta, and the β-rays were stopped by suitable absorbers. Data were automatically recorded during counting intervals of 32 minutes. The angle between the two counters could automatically be chosen to be ±90°, ±120°, ±135°, ±150°, and 180°. The 135° positions were not used in the measurements on Te^{126}. The photopeaks of interest were selected by single channel analyzers. In the measurements on Te^{126} the cascaded gamma rays were accepted in the same channel. There are no disadvantages with these discriminator settings. In Xe^{126}, however, the energies of the gamma quanta are rather close to 511 kev and as I^{126} is a positon emitter coincidences caused by annihilation radiation are very disturbing in the 180° counter angle position. This angle was thus omitted in the measurements on Xe^{126}.

Corrections for decay, asymmetric source position, and instabilities in the electronic apparatus were applied in the common way. Corrections for the finite solid counter angles were applied to the experimental coefficients of the Legendre polynomials [10]. The measurements have been carried out on solid polycrystalline sources of I_2O_5 in the measurements on Te^{126} and Xe^{126} and on metallic antimony in the Te^{122} measurement. The solid sources do not cause any objections from experimental viewpoint since the lifetimes of the first excited levels are certainly so short in all three cases that smearing out effects on the anisotropy due to electric quadrupole or other extranuclear interactions could be neglected. This effect is discussed in some detail in connection with the different nuclei.

The coefficients A_2 and A_4 in the Legendre expansion of the correlation function $W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$ for a $2+ - 2+ - 0+$ cascade can be written

$$A_2(\delta) = \frac{0.250 + 0.732\,\delta - 0.077\,\delta^2}{1+\delta^2} \quad \text{and} \quad A_4(\delta) = \frac{0.326\,\delta^2}{1+\delta^2}\,.$$

The functions $A_2(\delta)$ and $A_4(\delta)$ are shown in Fig. 1.

Te^{122}

The decay scheme proposed for the 2.8 days Sb^{122} is shown in Fig. 2 [2]. The angular correlation of the 686 kev–566 kev cascade in Te^{122} has been measured before [2, 3] but the measurements were repeated to check the earlier experiments.

Sb^{122} was produced by irradiating a sample of natural metallic antimony[1] in a reactor[2] for about an hour. The thermal neutron flux was of the order of $6.5 \cdot 10^{11}$

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[1] From J. T. Baker Chemical Co. who has given the following specification of the material: Sb 99.9 %, Fe 0.005 %, As 0.005 %, Pb 0.005 %, and Cu 0.003 %.

[2] The authors are indebted to AB Atomenergi, Stockholm, Sweden, for the irradiations in their reactor R1.

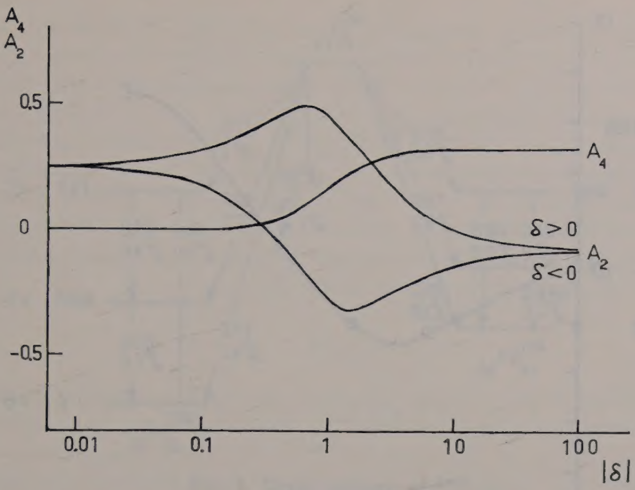

Fig. 1. A_2 and A_4 as functions of the mixing parameter δ for the spin sequence 2–2–0.

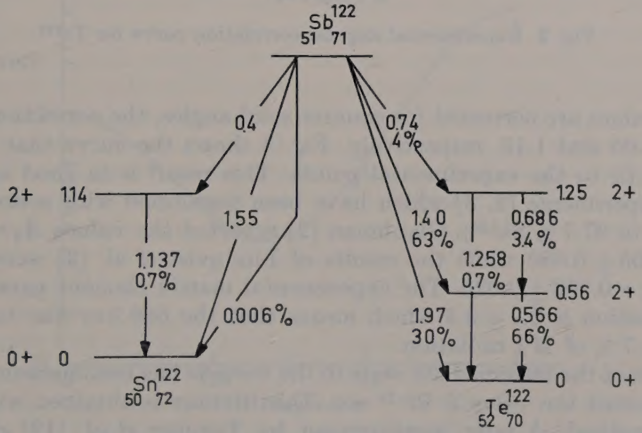

Fig. 2. Decay scheme of Sb^{122}.

$\text{neutrons/cm}^2 \cdot \text{sec}$. In natural antimony the isotopes Sb^{121} and Sb^{123} are of equal abundance. As the neutron capture cross section of Sb^{123} is approximately equal to that of Sb^{121} a small amount of the 64 days Sb^{124} activity is also produced. The decay of one sample was followed with a beta sensitive Geiger counter for about 45 days and it was observed that the amount of Sb^{124} was about 1.5 % of the Sb^{122} activity at the time when the neutron irradiation was interrupted. No radioactive impurities in the metal seemed to give measurable contribution to the activity, a fact which is in accordance with the specifications of the manufacturer of the antimony. To reduce the disturbing effect from the Sb^{124} activity, no source was used for more than 48 hours after the irradiation being interrupted.

The experimentally measured coefficients are $A_2 = 0.13 \pm 0.01$ and $A_4 = 0.27 \pm$

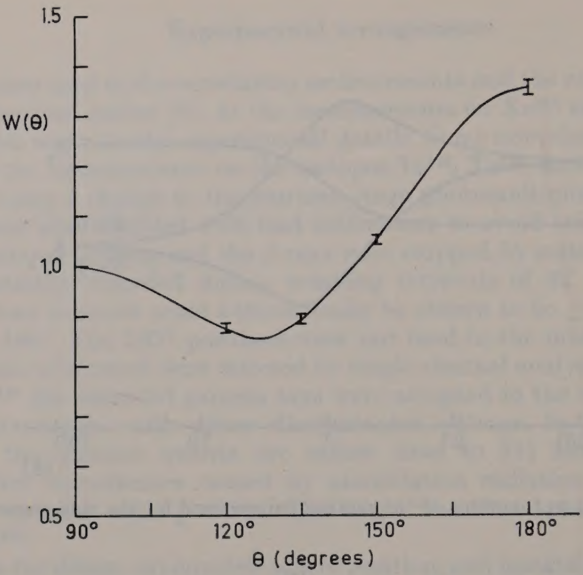

Fig. 3. Experimental angular correlation curve for Te^{122}.

0.02. These values are corrected for counter solid angles, the correction factors being as small as 1.05 and 1.15, respectively. Fig. 3 shows the curve that represents the least squares fit to the experimental points. This result is in good agreement with the earlier experiments [2, 3] which have been performed with sources of enriched material (up to 97.7 % Sb^{121}). Glaubman [2] reported the values $A_2 = 0.158 \pm 0.061$ and $A_4 = 0.305 \pm 0.080$ while the results of Lindqvist *et al.* [3] were $A_2 = 0.140 \pm 0.015$ and $A_4 = 0.302 \pm 0.025$. The experimental matrix element parameter δ of the 686 kev transition is 3.7 ± 0.3 which means that the 686 kev line to 93 % consists of $E2$ and to 7 % of $M1$ radiation.

The lifetime of the intermediate state in the cascade has been measured by Coleman [11] who reported the value $2 \cdot 10^{-10}$ sec. This lifetime is obtained with the delayed coincidence method. A later measurement by Temmer *et al.* [12] performed with Coulomb excitation techniques gave the much shorter lifetime $1.4 \cdot 10^{-11}$ sec. Since such a large discrepancy exists between these two measurements it would be of interest to repeat the experiments, at least the one using the direct method. Anyhow the lifetime seems to be so short that any attenuation of the angular correlation due to extranuclear effects must be very difficult to observe.

Te^{126}

A decay scheme of I^{126} is proposed by Koerts *et al.* [4] and is shown in Fig. 4. This scheme differs very little from the one proposed by Perlman *et al.* [5]. The Te^{126} branch is fed from I^{126} by K-capture and positon emission. The energies of the cascaded gamma rays have been measured to be 0.75 Mev and 0.65 Mev. A cross-over transition of 1.42 Mev has also been found.

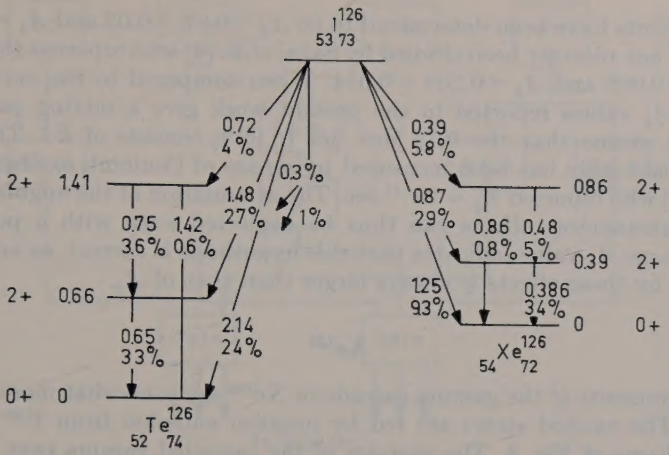

Fig. 4. Decay scheme of I^{126}.

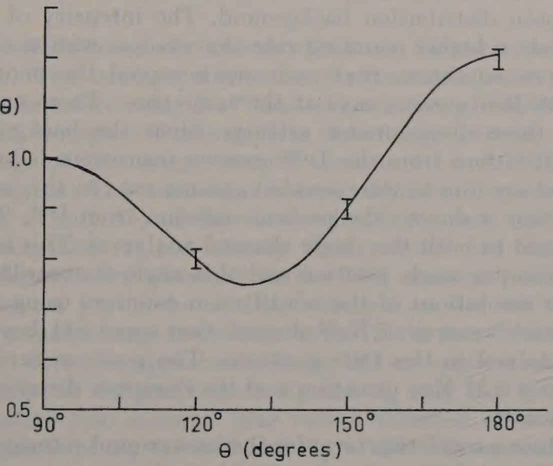

Fig. 5. Experimental angular correlation curve for Te^{126}.

I^{126} which is the parent nucleus of both Te^{126} and Xe^{126} was produced by irradiation of I_2O_5 with fast neutrons for about 250 μAh. The irradiation was performed in the Amsterdam cyclotron and the fast neutrons were produced by the reaction Be(d, n). The iodine sample was contained in a cadmium cylinder with a wall thickness of about 5 mm. This precaution was done to avoid that possible impurities in the iodine sample would give rise to disturbing activities. The isotope I^{128} produced by slow neutrons by the reaction $I^{127}(n,\gamma)I^{128}$ does not disturb the measurement since the half life is as short as 25 minutes.

The results of the angular correlation measurements are shown in Fig. 5 where the experimental points are plotted and a curve representing a least squares fit of the Legendre function $W(\theta) = \sum_{\nu} A_\nu P_\nu(\cos\theta)$ is drawn.

The coefficients have been determined to be $A_2 = 0.01 \pm 0.02$ and $A_4 = 0.35 \pm 0.04$. This cascade has recently been studied by Sakai *et al.* [6] who reported the coefficients $A_2 = 0.059 \pm 0.009$ and $A_4 = 0.268 \pm 0.014$. When compared to the curves in Fig. 1 the A_2 and A_4 values reported in the present work give a mixing parameter $\delta = 8.8^{+2.6}_{-1.7}$ which means that the 0.75 Mev line to 99 % consists of $E2$. The lifetime of the intermediate state has been measured by means of Coulomb excitation by Temmer *et al.* [12] who reported $T_{\frac{1}{2}} \sim 10^{-11}$ sec. The attenuation of the angular correlation caused by extranuclear effects can thus be neglected even with a polycrystalline source. The large A_4-value indicates that this hypothesis is correct, as an attenuation of A_4 caused by these effects is always larger than that of A_2.

Xe^{126}

The measurements of the gamma cascade in Xe^{126} are somewhat more complicated to perform. The excited states are fed by negaton emission from I^{126} according to the decay scheme of Fig. 4. The energies of the cascaded gamma rays are 0.48 and 0.39 Mev, respectively. These energies are lower than those of the gamma rays in the EC–β^+– branch of I^{126}. Accordingly the 0.48 and 0.39 Mev photopeaks are superimposed on a Compton distribution background. The intensity of the source was very low and to obtain a higher counting rate the window widths of the two single channel analyzers were so chosen that each one accepted the photopeaks of both the 0.48 and the 0.39 Mev gamma rays at the same time. There are however some disadvantages with these discriminator settings. Since the background consisting of the Compton distributions from the Te^{126} gamma transitions is high, some of the coincidences recorded are due to the cascaded gamma rays in this nucleus. Another disturbing contribution is due to the positon emission from I^{126}. The annihilation peak is partly accepted in both the single channel analyzers. This is of course most serious in the 180° counter angle position and this angle is accordingly omitted. A check of the angular resolutions of the scintillation counters using the annihilation radiation from a "thick" source of Na^{22} showed that some 511 kev–511 kev coincidences were still obtained in the 150° positions. The positons further give rise to coincidences between a 0.51 Mev quantum and the Compton distribution of the 0.65 Mev gamma transition.

In an effort to deduce a correction term for the background coincidences the experimental set-up was arranged according to the block diagram shown in Fig. 6. The single channel analyzers I and II were both adjusted to accept the 0.48 Mev–0.39 Mev cascaded gamma rays of Xe^{126} within the same channel widths and the window of analyzer III was positioned to accept the 0.75 Mev–0.65 Mev cascade of Te^{126}. In this way it was possible to record coincidences between the 0.48 Mev and the 0.39 Mev photopeaks as well as coincidences between the cascaded gamma rays of Te^{126}. In the latter case coincidences were recorded between the photo-peak in one counter and the Compton distribution in the other one and vice versa. With this method the anisotropy of the radiation from Te^{126} is automatically taken account of.

The number of coincidences due to the cascaded gamma rays of Xe^{126} can now be calculated. The measured quantities consisting of three single counting rates and two coincidence rates, all depend on a lot of variables, e.g. counter efficiencies and disintegration rate of the source. A system of five equations can thus be arranged. Besides the contribution from the photopeaks of interest these equations contain terms due to the annihilation and Compton radiation. The evaluation of

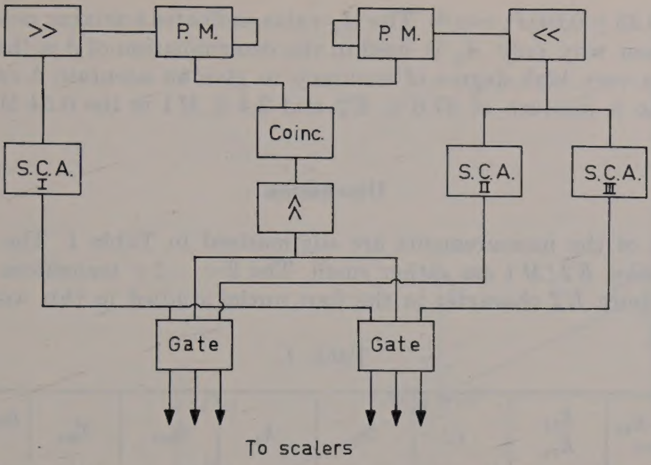

Fig. 6. Block diagram of the experimental arrangements used in the Xe^{126} measurements. (P.M. = photomultipier + preamplifier, S.C.A. = single channel analyzer.)

the number of coincidences of interest demands, however, some approximations of the equations. The counter efficiencies for the annihilation radiation was determined by a measurement using Na^{22} and the relative efficiencies for the 0.65 Mev photopeak and its Compton distribution in the energy interval selected by the discriminator settings of the single channel analyzers I and II (Fig. 6) was obtained from a Cs^{137} spectrum. The correction terms calculated for the angles 90°, 120°, and 135° amount to only 3 % of the total coincidence rate and the approximations done are thus acceptable. It has already been pointed out that some annihilation radiation coincidences were obtained in the 150° counter positions. Although the number is low, about 1 % of the number obtained in the 180° position, it is high enough to cause a rather large correction term. It was found that the uncertainties in the correction were too appreciable to permit an application to the 150° values.

In the calculation of the coefficients A_2 and A_4 only the three angles 90°, 120°, and 135° were taken into account. The values obtained after correction for finite solid counter angles were $A_2 = -0.03$ and $A_4 = 0.29$. The agreement with the values reported by Sakai *et al.* [6] ($A_2 = -0.07$ and $A_4 = 0.29$) is satisfactory. With regard to the uncertainties in A_2 and A_4 the value of the mixing ratio cannot be given more accurate than $|\delta| > 5$ which means that the $M1$ admixture in the 0.48 Mev gamma ray is less than 4 %.

The lifetime of the intermediate state in the cascade has not yet been measured. A theoretical calculation of the lifetime according to Weisskopf's formula [13] gives $5 \cdot 10^{-10}$ sec. As the lifetimes obtained with this single particle model generally are too long the value above may be looked upon as an upper limit. A measurement on a polycrystalline source is thus acceptable also for this nucleus.

Xe^{128}

A report of the correlation measurements on the 540 kev–455 kev cascade in Xe^{128} has already been published [9] and we refer for details to this report. It was found that the correlation was described by the function $W(\theta) = 1 - (0.18 \pm 0.02) \times$

$P_2(\cos\theta) + (0.35 \pm 0.04)P_4(\cos\theta)$. The A_2-value indicates a mixing ratio $\delta = -6.4 \pm 1.5$. The reason why only A_2 is used in the determination of δ is that A_4 must be known with a very high degree of accuracy to give an accurate δ-value. $\delta = -6.4$ corresponds to a mixture of 97.6 % $E2$ and 2.4 % $M1$ in the 0.54 Mev transition.

Discussion

The results of the measurements are summarized in Table 1. The variations of the mixing ratios $E2/M1$ are rather small. The $2+ - 2+$ transitions are found to be of almost pure $E2$ character in the four nuclei studied in this work. This is in accordance with the theoretical predictions for transitions between rotational levels in non-axial nuclei as given for example by Davydov and Filippov [14]. They have calculated the intensity ratio δ^2 to be

Table 1.

Nucleus	E_{22}–E_{21} Mev	$\frac{E_{22}}{E_{21}}$	γ	A_2	A_4	δ_{exp}	δ^2_{exp}	Percent $E2$	$\frac{T(E2)}{T(M1)}$
Te^{122}	0.69	2.2	26.5	+0.13	+0.27	3.7	13.7	93.2	60.6
Te^{126}	0.75	2.1	27.5	+0.01	+0.35	8.8	77.4	98.7	75.7
Xe^{126}	0.48	2.2	26.5	−0.03	+0.29	$> +5$ < -5	> 25	> 96	32.0
Xe^{128}	0.54	2.2	26.5	−0.18	+0.35	−6.4	41.0	97.6	43.2

$$\delta^2 = \frac{T(E2)}{T(M1)} = \frac{0.21\,k^2}{80}\left(\frac{e\,Z\,R_0^2}{\mu_0\,g_R}\right)^2$$

where $T(E2)$ represents the intensity of the emitted $E2$ radiation
$T(M1)$ represents the intensity of the emitted $M1$ radiation
k represents $\frac{E_{22} - E_{21}}{\hbar c}$
E_{22} represents the energy of the second excited 2+ state
E_{21} represents the energy of the first excited 2+ state
R_0 represents the nuclear radius
μ_0 represents $\frac{e\hbar}{2Mc}$
g_R represents the gyromagnetic ratio corresponding to collective motion of the nucleus

As a comparison Table 1 also shows the theoretically predicted mixing ratios. The deformation parameter γ calculated from the energy ratio E_{22}/E_{21} by means of the energy expressions

$$E_{21} = \frac{9\left[1 - \sqrt{1 - \frac{8}{9}\sin^2(3\gamma)}\right]}{\sin^2(3\gamma)}$$

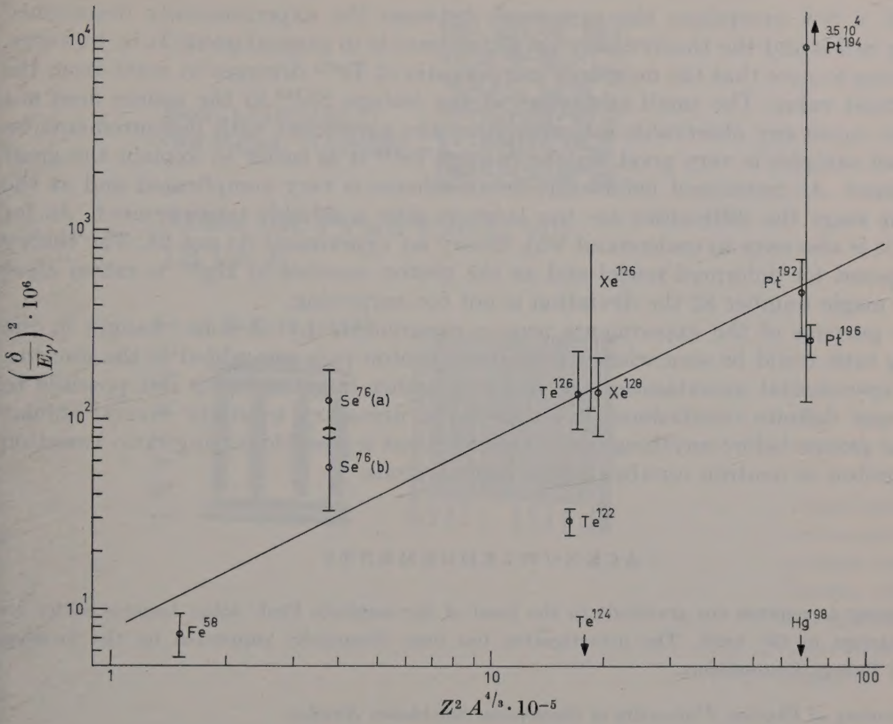

Fig. 7. Comparison of some measured values of $\left(\frac{\delta}{E_\gamma}\right)^2$ with the theory of Davydov and Filippov [14]. The solid line represents the theoretical predictions.

Fe^{58}: H. FRAUENFELDER, N. LEVINE, A. ROSSI, and S. SINGER, Phys. Rev. *103*, 352 (1956).
Se^{76}: a) T. LINDQVIST and I. MARKLUND, Nucl. Phys. *4*, 189 (1957);
b) C. F. COLEMAN, Nucl. Phys. *7*, 488 (1958).
Te^{122}: Present work.
Te^{124}: T. LINDQVIST and I. MARKLUND, Nucl. Phys. *4*, 189 (1957).
Te^{126}:, Xe^{126}:, Xe^{128}: Present work.
Pt^{192}: J. MRÁZ, Nucl. Phys. *4*, 457 (1957).
Pt^{194}: C. E. MANDEVILLE, J. VARMA, and B. SARAF, Phys. Rev. *98*, 94 (1955).
Pt^{196}: V. R. POTNIS, Indian J. Phys. *30*, 375 (1956).
Hg^{198}: C. D. SCHRADER, Phys. Rev. *92*, 928 (1953);
R. M. STEFFEN, Advances in Physics *4*, 293 (1955).

$$E_{22} = \frac{9\left[1+\sqrt{1-\frac{8}{9}\sin^2(3\gamma)}\right]}{\sin^2(3\gamma)}$$

is included in the table, too.

The δ-values obtained in these measurements agree fairly well with the theoretical curve drawn in Fig. 7. To give an idea of the possibilities of this theory in the interpretation of the experimental results, mixing ratios of some other nuclei are added to the figure.

With a few exceptions the agreement between the experimentally determined mixing ratios and the theoretically predicted ones is in general good. It is, however, surprising to note that the measured mixing ratio of Te^{122} diverges so much from the theoretical value. The small admixture of the isotope Sb^{124} in the source does not seem to cause any observable influence since the agreement with measurements on enriched samples is very good. In the case of Te^{124} it is easier to explain the great divergence. As mentioned before this decay scheme is very complicated and at the present stage the difficulties are too large to give a reliable measurement. As for Hg^{198} it is also easy to understand why theory an experiment do not fit. The theory is proposed for deformed nuclei and as the proton number in Hg^{198} is rather close to the magic number 82 the deviation is not too surprising.

The purpose of the experiments was to examine if any obvious changes in the mixing ratio could be seen when a neutron or proton pair was added to the nucleus. The experimental uncertainties are however rather large and it is not possible to draw any definite conclusions. It seems to be necessary to study several similar nuclear groups before anything could be said about a possible mixing ratio variation with proton or neutron number within finite regions.

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